4 CARBON SEQUESTRATION IN TERRESTRIAL ECOSYSTEMS

Vision

Research and development accomplishments by the year 2025 will lead to an ability to understand, predict, assess, measure, and implement substantially increased sequestration of carbon in soil and vegetation systems.

This chapter addresses the scope of the potential for sequestering carbon in the terrestrial biosphere. The aim of developing enhanced carbon sequestration in the biosphere is to enable a rapid gain in withdrawal of CO_2 from the atmosphere over the next 50 years in order to allow time for implementation of other technological advances that will help mitigate CO_2 emissions.

Carbon sequestration in terrestrial ecosystems is either the net removal of CO_2 from the atmosphere or the prevention of CO_2 net emissions from terrestrial ecosystems into the atmosphere. Carbon sequestration may be accomplished by increasing photosynthetic carbon fixation, reducing decomposition of organic matter, reversing land use changes that contribute to global emissions, and creating energy offsets through the use of biomass for fuels or beneficial products. The latter two methods may be viewed more appropriately as carbon management strategies. However, because of the need to integrate R&D issues related to ecosystem dynamics, we include information on these but focus primarily on sequestration.

The terrestrial biosphere is estimated to sequester large amounts of carbon (~2 GtC/year). Our vision is that we will increase this rate while properly considering all the ecological, social, and economic implications. There are two fundamental approaches to sequestering carbon in terrestrial ecosystems: (1) protection of ecosystems that store carbon so that sequestration can be maintained or increased and (2) manipulation of ecosystems to increase carbon sequestration beyond current conditions. We emphasize manipulative strategies and the R&D necessary to understand, measure, implement, and assess these strategies.

Soil—The Earth's Living Membrane

Soil, which has been described as a living membrane between bedrock and the atmosphere (CNIE 1998), is actually a diverse ecosystem containing microorganisms and many types of invertebrates and vertebrates as residents. Soils are critical to plant production, but they also are essential for carbon sequestration (soils currently contain ~75% of the terrestrial carbon). Soils in which high levels of carbon are present as soil organic matter (SOM) exhibit improved nutrient absorption, water retention, texture, and resistance to erosion, making them particularly useful for both plant productivity and sequestration. R&D is needed to better manage soils to increase carbon sequestration.

Storage of carbon in belowground systems is the best long-term option for carbon storage in terrestrial systems because most SOM has a longer residence time than most plant biomass. SOM is a complex mixture of compounds with different residence times. The more stable compounds are the most important for carbon sequestration because they have turnover times of hundreds to thousands of years. R&D can determine ways to increase the presence of the most stable compounds in SOM.

Prevention of erosion can be a major contributor to carbon sequestration. The Food and Agricultural Organization (FAO 1992) estimates that 25 billion tons of soils are lost through erosion each year. The Committee for the National Institute for the Environment (CNIE 1998) provides a dramatic description for this lost soil: "If dropped on Washington, D.C., this amount of soil would cover the city under more than 100 meters, burying the Capitol dome." If this soil contained an average of 4% soil organic carbon, that would be equivalent to emissions of roughly 1 GtC/year (CNIE 1998). Even though erosion cannot be completely prevented, research may identify possible strategies to enhance the capture and longevity of SOM released by erosion and transported by rivers into wetlands and coastal areas.

Land-use management and agricultural practices have great potential to sequester carbon by protecting soils. About one-third of the current 1.5 billion tonnes of carbon emitted to the atmosphere because of changes in tropical land use is from oxidation of soil carbon. It is estimated that 40 to 60 billion tonnes of carbon may have been lost from soils as the result of forest clearing and cultivation since the great agricultural expansions of the 1800s. When land is converted from natural perennial vegetation and cultivated, SOM generally declines by 50% in the top 20 cm of soil and 20 to 30% in the top meter of soil. Because less organic matter is introduced to the soil and because soil aggregates are destroyed (causing the loss of physical protection mechanisms that trap soil carbon), SOM declines significantly. In addition, cultivated soil is exposed to the air, so, during decomposition by soil organisms, the SOM is oxidized and the carbon carried off as CO_2. With good management to protect soils and the development of methods to improve texture of soils so they trap more carbon, it may be possible to exceed the original native SOM content of many soils.

In this chapter, we review the inventories of carbon in terrestrial ecosystems and the roles of the biosphere in the global sequestration process and then estimate the potential for carbon sequestration in each of them (Sects. 4.1 and 4.2). We next summarize the current capabilities in carbon sequestration (Sect. 4.3). The gap between the potential for carbon sequestration and the current capabilities establishes the drivers for R&D needs. Section 4.4 begins the actual road map. It starts at the system level with our vision for carbon sequestration in the terrestrial ecosystem. From this, we establish three objectives (Sect. 4.4.1) and then propose strategies that will help in meeting those objectives (Sect. 4.4.2). The final leg of the road map is to identify the R&D that is required to realize the strategies (Sect. 4.4.3).

The world's terrestrial environment comprises a wide diversity of ecosystem types that can be categorized into several biomes to address unique aspects of their carbon sequestration potential. A single, realistic set of R&D needs covering all issues in these highly variable systems cannot be stated. Therefore, we developed a primary set of R&D needs that represent cross-cutting topics. These R&D needs, which are broadly applicable to several of the major ecosystems, are discussed in the main body of this chapter. Appendix B contains information specific to each of the ecosystems.

Multiple Benefits of Terrestrial Sequestration of Carbon

Increasing the storage of carbon in vegetation and soils could offer significant accompanying benefits: improved soil and water quality, decreased nutrient loss, reduced soil erosion, better wildlife habitats, increased water conservation, and more biomass products. Restoring wetlands to sequester larger quantities of carbon in sediment will also preserve wildlife and protect estuaries. Understanding how to increase soil carbon stocks in agricultural lands is critical to increasing sustainability of food production. Finally, creating conditions for higher plant productivity and accumulation of soil carbon to increase carbon sequestration will have the side benefit of restoring degraded ecosystems worldwide.

Increases in soil carbon sequestration alone can provide significant benefits by delaying the need for more technically complex solutions. Edmonds et al. (1996, 1997) estimated that, for agricultural soil carbon only, 35 years of time might be "bought" (potentially saving at least $100 million) before major adjustments in the world's energy production system would be required to meet a goal of 550 ppmv atmospheric CO_2. As a result, over the next quarter century, other carbon management options could be evaluated and implemented.

4.1 TERRESTRIAL ECOSYSTEMS: NATURAL BIOLOGICAL SCRUBBERS

The total amount of carbon "stored" in terrestrial ecosystems is large (~2000 ± 500 GtC). Table 4.1 shows estimates of the distribution of this carbon among the major ecosystems of the world. Carbon sequestration in these terrestrial ecosystems will be enhanced by increasing the amounts of carbon stored in living plant matter, roots, and soil carbon (inorganic and organic) and in long-lived materials that contain woody matter, or by processing wood into long-lived carbon products. Net removal of CO_2 from the atmosphere by terrestrial ecosystems (~2 GtC/year) occurs when plant photosynthesis exceeds all processes of consumption and respiration, resulting in above-ground plant growth and increases in root and microbial biomass in the soil. Plant matter is consumed when it is eaten, dead or alive, by an animal. In addition, plants return stored carbon to the atmosphere through respiration, as do animals

Table 4.1. Global estimates of land area, net primary productivity (NPP), and carbon stocks in plant matter and soil for ecosystems of the world

Ecosystem	Area (10^{12} m^2)	NPP (gC/m^2/year)	NPP (Pg C/year)	Plant C (g/m^2)	Plant C (Pg)	Soil C[a] (g/m^2)	Soil (Pg)	Total (Pg)
Forest, tropical	14.8	925	13.7	16500	244.2	8300	123	367
Forest, temperate and plantation	7.5	670	5.0	12270	92.0	12000	90	182
Forest, boreal	9.0	355	3.2	2445	22.0	15000	135	157
Woodland, temperate	2.0	700	1.4	8000	16.0	12000	24	40
Chaparral	2.5	360	0.9	3200	8.0	12000	30	38
Savanna, tropical	22.5	790	17.8	2930	65.9	11700	263	329
Grassland, temperate	12.5	350	4.4	720	9.0	23600	295	304
Tundra, arctic and alpine	9.5	105	1.0	630	6.0	12750	121	127
Desert and semi-desert, scrub	21.0	67	1.4	330	6.9	8000	168	175
Desert, extreme	9.0	11	0.1	35	0.3	2500	23	23
Perpetual ice	15.5	0	0.0	0	0.0	0	0	0
Lake and stream	2.0	200	0.4	10	0.0	0	0	0
Wetland	2.8	1180	3.3	4300	12.0	72000	202	214
Peatland, northern	3.4	0	0.0	0	0.0	133800	455	455
Cultivated and permanent crop	14.8	425	6.3	200	3.0	7900	117	120
Human area	2.0	100	0.2	500	1.0	5000	10	11
Total	150.8		59.1		486.4		2056	2542

[a]Soil C values are for the top 1 m of soil only, except for peatlands, in which case they account for the total depth of peat.

Source: Amthor et al. 1998.

through their waste or death and decay. When a plant sheds leaves and roots die, this organic material decays, adding carbon to the soil. Soil carbon is lost to the atmosphere through decomposition by soil organisms (e.g., fungi and bacteria). This process also mineralizes organic matter, making available the nutrients needed for plant growth. The total amount of carbon stored in an ecosystem reflects the long-term balance between plant production (inputs) and all respiration and decomposition (losses).

Biological transformation of carbon has been, and quite likely will continue to be, a primary mechanism for removing CO_2 from the atmosphere. This is reflected in the standing stock of vegetation and the accumulation of soil organic matter. Methods that rely on biological transformation can play a central role in the management of carbon sequestration in the future. This biospheric carbon sequestration is essentially a huge natural biological scrubber for all emission sources (e.g., fossil fuel plants, cement plants, automobiles). The estimated value of 2 GtC/year removed from the atmosphere each year by the earth's mantle of vegetation is the net ecosystem production. This value is uncertain because it is an estimated difference between photosynthesis and respiration—both very large fluxes and highly uncertain (Chap. 1). We can "observe" the contemporary, world-wide *net difference* between global carbon uptake by photosynthesis (P) and releases by respiration (R) through measuring annual changes in atmospheric CO_2 and accounting for oceanic carbon dynamics. However, we cannot use this information to assess how the biosphere will regulate atmospheric CO_2 in the future. This is because the P:R ratio is highly sensitive to environmental variables such as temperature, moisture, and nutrient availability and differs among ecosystems. If atmospheric CO_2 increases enough to cause climate change, the global P:R ratio may change in ways that we cannot now predict accurately. Small changes in these large numbers could dwarf any carbon management strategy imposed by humans.

4.2 POTENTIAL FOR CARBON SEQUESTRATION

The biomes that make up the terrestrial ecosystem are categorized in Table 4.2. The estimates of potential carbon sequestration include the current natural rate of carbon sequestration, which totals about 2 GtC/year. Note that achieving the potential indicated in the table, particularly the higher numbers, may imply an intensive management and/or manipulation of a significant fraction of the globe's biomes. The table also does not reflect estimates of economic, energy, social, or environmental costs to achieve such a rate, which could be unacceptably large for higher numbers. The values in Table 4.2 are large and exceed most other estimates. It is important to remember that these assume R&D advances will occur to allow us to optimize carbon sequestration beyond what is thought to be achievable with current best management practices.

Estimating the potential for increasing carbon sequestration in terrestrial ecosystems is difficult because the biogeochemical dynamics that control the flow of carbon among plants, soils, and the atmosphere are poorly understood. Additionally, there will be socioeconomic issues, energy costs (such as possible hydrocarbon feedstock for fertilizers), and potential ecological consequences that would

Table 4.2. The categorization of biomes used in this road-mapping exercise
Global potential carbon sequestration rates were estimated that might be sustained over a period of 25 to 50 years

Biomes	Potential CS (GtC/year)[a]
Agricultural lands	0.85-0.90[b]
Biomass croplands	0.5-0.8[c]
Grasslands	0.5[d]
Rangelands	1.2[e]
Forests	1-3[f]
Urban forest and grasslands	*g*
Deserts and degraded lands	0.8-1.3[h]
Terrestrial sediments	0.7-1.7[i]
Boreal peatlands and other wetlands	0.1-0.7[j]
Total	5.65-10.1

Assumptions

[a]R&D allows improvements in carbon sequestration implementation; no reallocation of land use from Table 4.1 except for 10-15% of agricultural land to biomass crop lands. The totals include the current natural rates.

[b]Soil carbon only; recovery of an amount equivalent to what was lost from native soils prior to agricultural use; implementation of best available management (e.g., no-till, intensified production and residue inputs, intensified rotations with crop rotation, double cropping, greater use of perennials) and new technologies such as discussed in the chapter with some CO_2 fertilization.

[c]An average annual aboveground productivity level of 13.2 Mgdwt/ha/year (6t/ac). Belowground storage of carbon is 1.75 MgC/ha/year and is assumed to be "permanent" and not to provide any negative feedback on further storage. Short rotation woody crop and perennial grass production are assumed to provide equivalent carbon storage benefits. The energetic costs of producing and harvesting switchgrass result in a biomass energy return ratio (energy in harvested biomass divided by production energy costs) of 12.3 and an energy gain of 343% for ethanol production. The carbon gain from substitution of ethanol for gasoline (2.48 MgC/ha/year) after subtracting carbon costs of production (0.60 MgC/ha/year) and adding an average belowground sequestration rate of 1.75 MgC/ha/year provides an annual carbon savings of (2.48 + 1.75- 0.60) = 3.60 MgC/ha/year. Trees and grasses are assumed to be equally efficient at net carbon production and sequestration, and it is assumed that production of ethanol and electricity provide equivalent net benefits in terms of carbon savings. A conversion of 10% of current crop to biomass crops for energy represents a realistic target; under more favorable conditions a 15% conversion might be achievable on a world basis.

[d]Intensification of management with fertilization, controlled grazing, and species improvements; 25% increase in belowground carbon stocks; linear increases through 2050.

[e]Total increase of 27 GtC through 2050; rehabilitation of degraded rangeland and fertilization by increasing CO_2.

[f]Watson et al. (1996) estimate 1-1.6 GtC/year (their Table 14) and include above- and belowground vegetation, soil carbon, and litter. Their estimate does not include R&D to increase carbon sequestration. Trexler (1998) suggests a rate of 2 GtC/year may be plausible. With focused R&D, both these values may be exceeded.

[g]No estimate available.

[h]From Table 23 of Lal, Hassan, and Dumanski (1998). Soil carbon emphasis; erosion, desertification, and global warming effects are controlled; includes restoration of lands; reclamation of salt-affected soils; agricultural intensification on nondegraded lands (~0.015 GtC/year); and fossil fuel carbon offset of ~0.2 GtCg/year; includes accretion of inorganic carbonates.

[i]Estimate from Stallard (1998), which is for current sequestration, increased by 15% to account for benefits from R&D on approaches to better sequester carbon in sediments. We do not imply increasing erosion, but better managment of existing and future sediments. Although they are not truly an ecosystem, we categorize sediments because of the large potential to store carbon and the recent acknowledgement that they may be a key part of the carbon inventory.

[j]Assumes the impact of recent global warming on net carbon balance can be reversed (Oechel et al. 1993) and the future warming can be controlled (Goulden et al. 1998); sequestration of plant carbon will be increased by management of soil carbon and perhaps limited conversion to forest or grassland vegetation where ecologically acceptable.

need to be compared with the benefits of sequestration or other carbon management options. However, the upper limit on terrestrial sequestration could be large should extraordinary measures be needed at some time in the future.

Using the estimated distribution of carbon stored in the major ecosystems of the world (Table 4.1), we projected possible rates of carbon sequestration, assuming advances from R&D and a global emphasis on carbon sequestration. These are presented for each of the nine biomes in Table 4.2. Although land-use changes, such as growing new forests and decreasing deforestation, have great potential to mitigate increasing carbon emissions, the carbon sequestration potential for such optimization across global systems requires a more comprehensive and systematic analysis than was possible during this effort. The major land-use change incorporated into the present analysis was an assumption that the results of R&D would allow 10 to 15% of agricultural crop land to be converted to biomass energy crop production. The estimate for deserts and degraded lands also contains several assumptions with respect to land-use change (Lal, Hassan, and Dumanski 1998). With the caveat of the assumptions noted above, and in Table 4.2, it is possible that ~5 to 10 GtC/year could be sequestered globally when all ecosystems are considered, compared with current rates of ~2 GtC/year. One of the key research questions is how long these rates of carbon sequestration in these biomes could be maintained. Also, there clearly will be some maximum capacity for sequestration, but that capacity is far from certain. Refining such estimates should be one of the R&D tasks undertaken. In refining estimates of sequestration potential, one could envision a two-dimensional matrix of "intensity of carbon sequestration effect" plotted against "management intensity." With this approach, many ecosystems would be represented more than once. For example, protection of wetlands would be low-management-intensity and high-potential, while creation of new wetlands would be high-management-intensity and high-potential.

Although perhaps surprisingly large, these relatively high ranges of potential carbon sequestration may not be unreasonable. For example, a 5% increase in the total carbon contained in global terrestrial ecosystems over a 25-year period would sequester >100 GtC. Sequestering 100 GtC over 25 years requires increasing the rate of carbon sequestration in terrestrial ecosystems (~2000 GtC) by an average of only 0.2% per year—roughly half what our provocative estimates project as possible.

Strategies for sequestration a few decades from now will be implemented in a world different from today's. Human responses to climatic change and other environmental issues, population growth, economic development, and technological change may well lead to changes in patterns of land use, settlement, and resource management. It seems unlikely that carbon sequestration will be the highest-priority use for any land; instead, sequestration will have to be compatible with a host of other demands on ecosystem goods and services.

There are some limitations and uncertainties related to carbon sequestration potential in terrestrial ecosystems. First, it is critical at the outset to take a whole ecosystem approach. Having the capability to assess potential impacts on a particular ecosystem from an emphasis on sequestering carbon is a major need. For example, the dynamics of carbon storage and allocation are at present not well known under temperature, moisture, and nutrient conditions of a changing climate. Second, carbon sequestration strategies may have consequences beyond simply increasing carbon storage. Increasing organic matter in wetlands could result in higher emissions of methane, a greenhouse gas with a 20 times higher contribution to global warming than CO_2, although hydrologic controls or increases in the fraction of recalcitrant organic matter could offset this process. Converting croplands to grasslands may increase emissions of nitrous oxide (N_2O), another greenhouse gas, to the atmosphere (Marland et al. 1998).

Third, land use and sequestration actions also could alter the flow of micronutrients. For example, as a result of controls on erosion, might the fluxes of phosphorous and nitrate in aquatic systems increase or decrease to levels that cause ecological impacts? Strategies to “improve” carbon sequestration in deserts through increases in drought-tolerant vegetation could lead to decreased fluxes of wind-blown nutrients such as iron, with possible adverse impacts on the ability of the ocean to sequester carbon through iron-fertilized phytoplankton (Chap. 3). Thus research should support the development of effective yet flexible strategies for carbon sequestration and seek understanding of the interplay of these strategies with other human activities and goals.

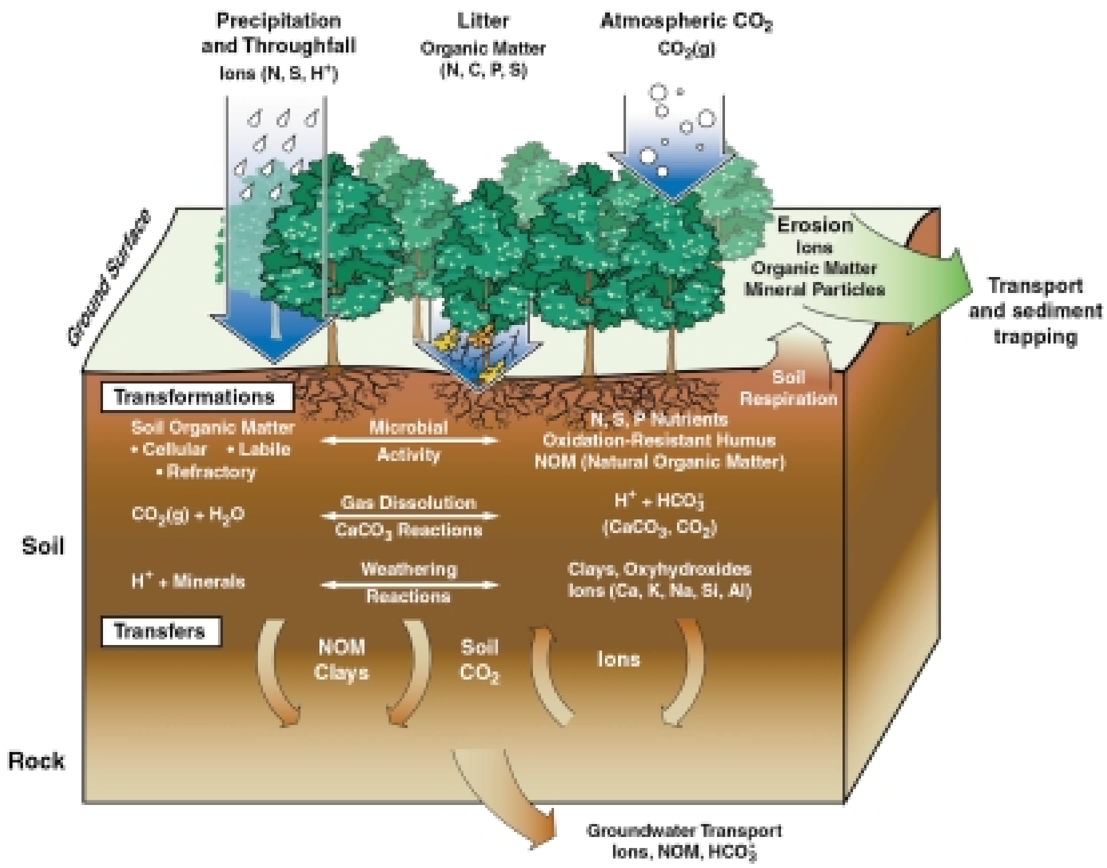
4.3 CURRENT CAPABILITIES

Historically, little emphasis was given to developing strategies for carbon sequestration. Rather, other priorities and practices actually promoted carbon release. For example, in the United States, 50% of the original wetlands have been lost. Fortunately, the trend now is to protect or even increase wetland acreage to preserve ecosystems and maintain biodiversity. Globally, losses of wetlands are not well documented but probably are as great as they are in the United States on a percentage basis. Changes in forest stocks and land clearing are continuing throughout most of the world.

Implementation of no-till practices, return of residues to soil, and the activities of the Conservation Reserve Program are increasing the amount of carbon in agricultural systems. (The main reason: the soil is less exposed to air, so less soil carbon is oxidized and carried off as CO_2.) Estimates suggest that the potential for soil carbon sequestration may be 8 to10 teragrams per year (Tg/year, or 10^{12} g/year), offsetting a third of the 28 TgC/year of fossil carbon emissions from agricultural production (Lal et al. 1995; Lal, Kimble, and Follett et al. 1998). The concomitant increase in below-ground carbon can be substantial; there is some evidence that levels of soil organic carbon have doubled over the past 20 years in the upper 18 cm of soil placed in the Conservation Reserve Program (Gutknecht 1998).

The cutting of forests of eastern North America in the previous century is now being replaced by forest regrowth, and North America might even be a sink for carbon at this time (Fan 1998). Forests in the United States are being

Soil Processes that Influence Carbon Fate and Transport



The dynamics of carbon transformations and transport in soil are complex and can result in either carbon sequestration or even increased emissions of CO_2. Bicarbonate (HCO_3) ions dissolved in water could be sequestered if the dissolved carbonate enters a deep groundwater system that has a residence time of hundreds to thousands of years. Natural organic matter is another type of soil carbon that could be transported to deep groundwater systems. Natural organic matter can be mobilized during intense precipitation following prolonged dry periods, based on observations at Walker Branch Watershed in Oak Ridge. This carbon-rich material may be sequestered if it is transported to deeper groundwater systems or deposited deeper in soil. Thus there may be opportunities to encourage geohydrologic systems to promote the deep transport of carbon into groundwater systems.

managed to maintain cover, increase water storage, and retain litter. Globally, however, there are still major challenges to slowing the rate of deforestation. The challenge is to reverse deforestation to gain 1.4 GtC/year and go beyond that to perhaps >2 GtC/year. Trexler (1998) and Sohngen et al. (1998) summarize modeling studies that suggest forests could sequester from 200 to 500 GtC by 2090.

Although the use of biomass as an alternative fuel supply is not implemented yet on a large scale, the R&D program is succeeding in showing the promise of this renewable energy technology. Perhaps sequestration of 0.5 to 0.8 GtC/year from crop-to-biofuel conversion could be achieved by converting 10 to 15% of agricultural cropland to energy crops. It is important to point out that the use of biomass products can have additional benefits beyond sequestration in carbon management. For example, they may replace a product that is energy-intensive to manufacture (e.g., cotton can replace fiberglass as insulation), or they may be more energy-efficient in performance (e.g., plastic car panels manufactured from biomass feedstock are lighter than steel).

For tundra and taiga, unfortunately, the trend is in the wrong direction. These areas are being impacted so as to become carbon sources rather than sinks. Desertification and land degradation are still increasing globally, and little emphasis is being placed on how to use these areas for carbon sequestration. Lal, Hassan, and Dumanski (1998) and Lal, Kimble, and Follett et al. (1998) show that soil carbon sequestration can be a major benefit in these systems. Urbanization eliminated 10 million hectares (ha) of agricultural and forested land in the United States between 1960 and 1980. These highly impacted environments offer interesting opportunities. The density of carbon under these “intensively managed” systems (e.g., lawns with trees) is high—attributable to the high rates of fertilization and irrigation, with nitrogen oxide pollutants perhaps playing a minor role. Ancillary benefits from urban forestation might include local cooling effects and water retention that would reduce emissions from fossil fuel use.

Batjes (1999) discusses management options to optimize soil carbon sequestration. He discusses many of the biomes listed in Table 4.2 and the strategies available to increase carbon sequestration, as well as the intensity of management options to achieve sequestration. It is clear that there are near-term beneficial practices that can be followed to recover some of the carbon lost from past practices and to protect important ecosystems. These should be implemented as much as is feasible. However, these alone cannot meet the vision for carbon sequestration. More specific and focused efforts will be required. The purpose of this road map is to lay out possible R&D options that may allow us to go beyond recovery and protection. R&D should be initiated to create options that will beneficially optimize carbon sequestration in terrestrial ecosystems.

4.4 TERRESTRIAL ECOSYSTEM SCIENCE AND TECHNOLOGY ROAD MAP

Figure 4.1 summarizes the entire science and technology road map for terrestrial ecosystems. The system goals for terrestrial ecosystems are left unknown. One of the first R&D needs

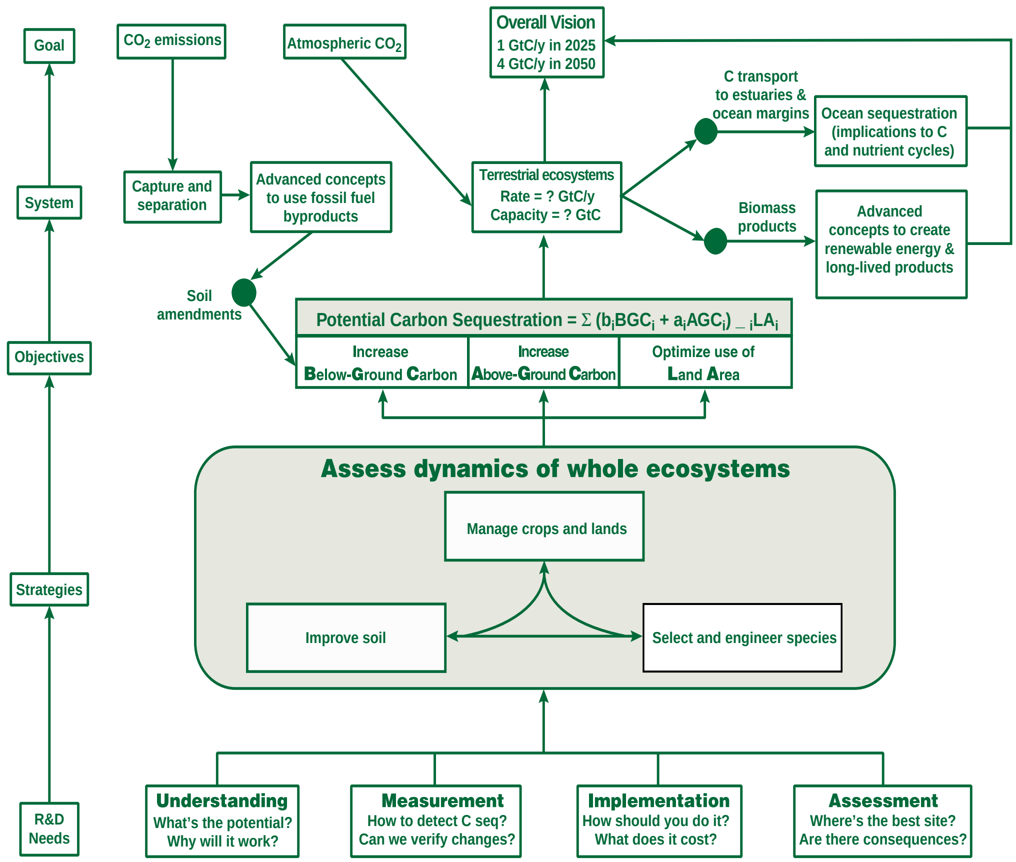


Fig. 4.1. Overall system view of the science and technology road map for the terrestrial ecosystems.

is to refine these targets and assess the feasibility of reaching the goals (i.e., the limits on sequestration rate and capacity). As research is accomplished over the 20–50-year time period, these estimates can be refined.

Figure 4.1 illustrates some of the key linkages among terrestrial sequestration and other options at the Goal & System Levels:

- CO_2 emissions could be captured and converted into byproducts that could be used as amendments to improve ecosystems (e.g., land reclamation or forest fertilization).
- Changing terrestrial ecosystem carbon cycles impact carbon transport to estuaries and ocean margins. Increasing or decreasing nutrient inputs to these systems has significant implications.
- Using biomass to create long-lived products or fuel is a critical part of any overall carbon management strategy.

Recall the importance of looking at the major ecosystems of the world, as was discussed earlier. The system level is expanded in Fig. 4.2 to illustrate a detailed view of the road map that includes the major ecosystems. In this figure and following road map figures, the level of the road map being discussed in detail is expanded at the far left of the figure.

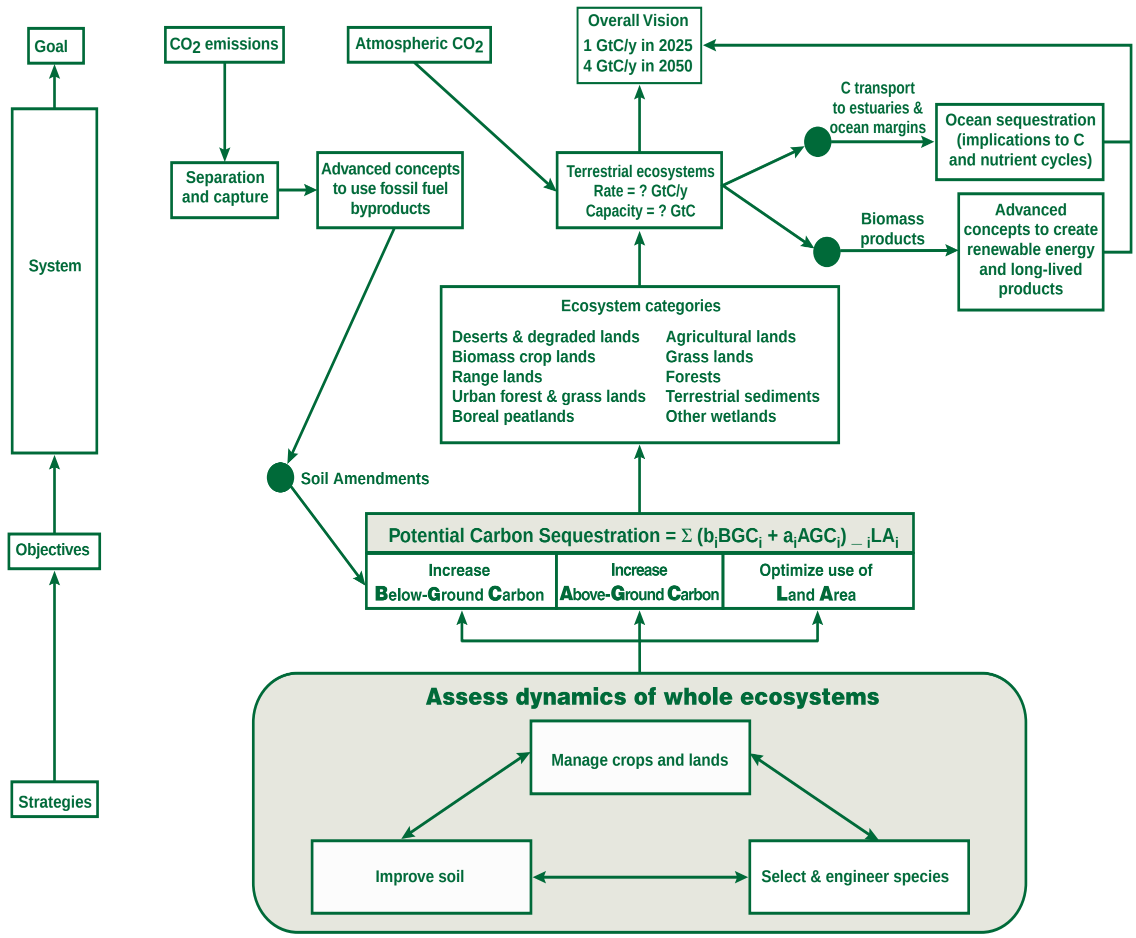


Fig. 4.2. Detailed view of the system level showing the ecosystem categories that are part of the overall system.

After establishing a vision, objectives are defined to meet that goal. Sect. 4.4.1 and Fig. 4.3 present the three technology objectives that, if met, would allow the vision to be achieved. After objectives have been established, a variety of strategies can be developed that would focus on meeting the objectives (see Sect. 4.4.2 and Fig. 4.4). The final step is to identify R&D to support implementation of the strategies (see Sect. 4.4.3 and Fig. 4.5).

4.4.1 Objectives

Our carbon sequestration system has three objectives (Fig. 4.3): increase the amount of carbon in below-ground systems (soil or sediment), increase the carbon in above-ground biomass, and/or manage land area with an emphasis toward carbon sequestration. A simplified representation of how one might quantify the potential carbon sequestration (PCS) is

$$PCS = \Sigma\,(b_i BGC_i + a_i AGC_i) \times c_i LA_i \qquad (1)$$

where

a_i = potential increase in above-ground carbon in the i^{th} ecosystem;

b_i = potential increase in below-ground carbon in the i^{th} ecosystem;

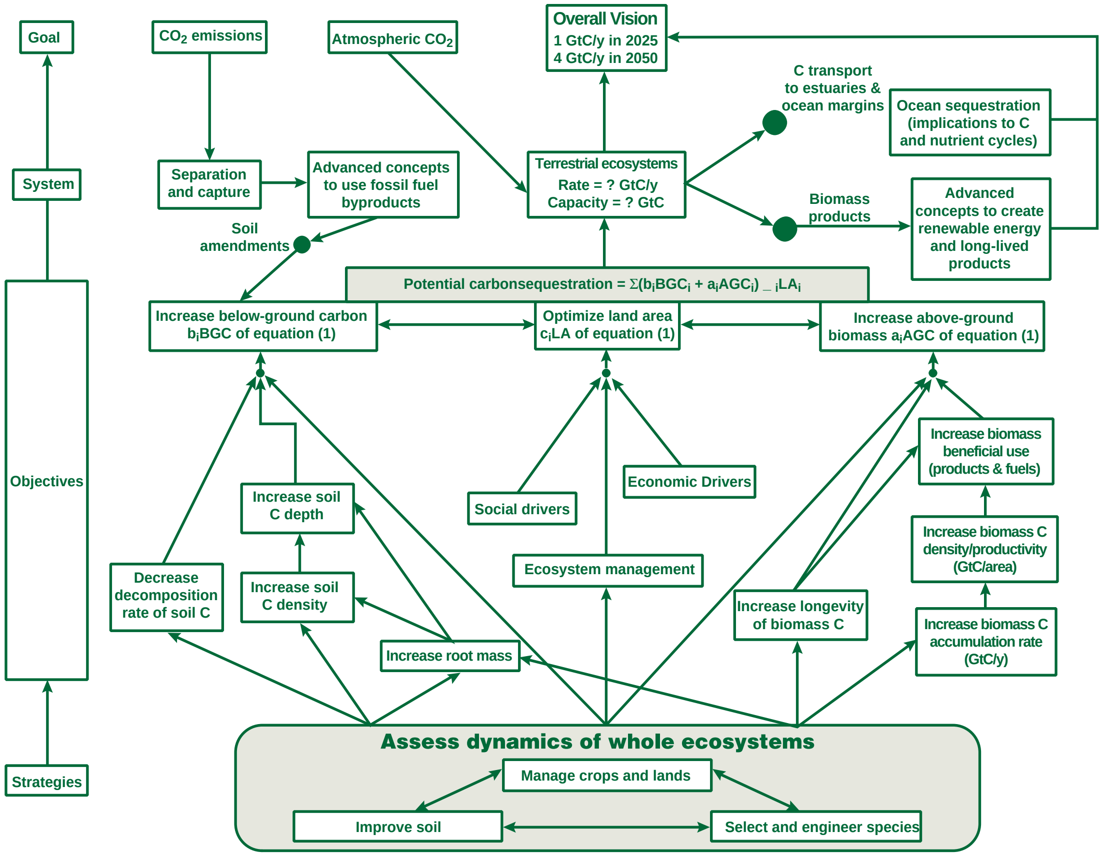


Fig. 4.3. Detailed view of the objectives level showing the various components that feed into the three primary objectives that are described in equation (1).

c_i = potential change in land area due to management for carbon sequestration in the i^{th} ecosystem;

AGC_i = above-ground carbon; biomass of the i^{th} ecosystem in the index year;

BGC_i = below-ground carbon; root biomass + soil carbon (organic and inorganic) in the i^{th} ecosystem in the index year;

LA = land area of each ecosystem in the index year.

To arrive at a global total for potential carbon sequestration, we must obtain the above- and below-ground carbon inventory for each ecosystem in the index year, multiply that number by the potential change coefficient, assume an optimization of land use to maximize carbon storage potential, and sum across all ecosystems.

Although represented as independent variables, the three terms (above-ground carbon, below-ground carbon, and land area) are obviously tightly coupled. There is great synergism among plant biomass and soil organic carbon. Changes in the allocation of land area between different ecosystem types (e.g., conversion of annual cropland to biomass plantations) can increase above-ground carbon, which can lead to increases in below-ground carbon. The rate of increase in above-ground carbon will initially be much faster than increases in below-ground carbon, but the rates of change will depend on the type of land use reallocation. In addition, major changes in both rates are possible within ecosystem types (independent of land reallocation) through various types of management interventions. We use the equation simply as a means to highlight objectives for carbon sequestration and to drive the development of R&D needs.

Using potential carbon sequestration (Eq. 1) to define sequestration options, we discuss each of the variables separately. The detailed view of the objectives in Fig. 4.3 illustrates four ways to increase below-ground carbon:

- increase the depth of soil carbon
- increase the density of carbon (organic and/or inorganic) in the soil
- increase the mass and/or depth of roots
- decrease the decomposition rate of soil carbon

One key link to another technology system is the possible use of byproducts created by advanced chemical or biological methods as soil additions to increase organic content, water retention, and protection of organic matter, and to improve the texture of the soil so that it can hold more carbon. An example might be creation of “smart fertilizers” or the use of mixtures of minerals (e.g., carbonates, silicates, and oxides) formed at fossil fuel power plants (Chap. 7) blended with biosolids such as sewage sludge. See the “Soil Amendments” link between advanced concepts to below-ground carbon in Fig. 4.1.

For the above-ground system, there are also four ways to increase carbon sequestration (Fig 4.3):

- increase the rate of accumulation of above-ground biomass
- increase the density of total biomass per area and/or the density of carbon in the above-ground biomass
- increase the longevity of biomass carbon (decrease decomposition rate)
- increase beneficial use of biomass carbon in long-lived products

An important component from the above-ground carbon term is the use of biomass products. Increasing the density of total biomass or the accumulation rate offers high carbon sequestration potential. However, storage due to increased plant productivity is most efficient if the carbon is moved to a long-term pool, such as long-lived woody biomass or soils. Another alternative is to substitute products manufactured from biomass for products that are made using fossil fuels, addressing both sequestration and management. Obvious examples that address both carbon management and sequestration include biofuels and wood products. Less obvious but perhaps important examples that are focused on carbon sequestration might include the use of biomass products in structural materials (e.g., cement) or combined with other materials to create new soils. These are illustrated by the “Biomass Product” link to “Advanced Chemical and Biological” at the system level (Fig. 4.2).

The land area term is the large multiplier. As seen by the large areas in Table 4.1, in some ecosystems, a small change in carbon content could result in large increases in total carbon sequestered. Although the total land area of the world cannot be increased, R&D might allow the land area term to increase total carbon sequestration by optimization across the following:

- social drivers
- economic drivers
- ecosystem management drivers

Optimization among ecosystems for carbon sequestration will be a complex function. Research in this area should include issues such as transforming land from low carbon sequestration uses to high carbon sequestration uses, as well as reversing land use changes that have made land areas into sources of CO_2 emissions.

4.4.2 Strategies

The next level of the road map addresses strategies (Fig. 4.4) that support the objectives. The overriding objective for terrestrial ecosystem carbon sequestration is to optimize net ecosystem exchange and ensure that the increased carbon is stored in long-lived vegetation, soil, or products. Therefore, strategies must be considered at the ecosystem and regional scales, because it is at these scales that management practices will be implemented.

There are three specific strategies that support the objectives (Fig. 4.4): (1) manage crops and lands, (2) improve soil, and (3) select and engineer species. These are closely coupled, and they must be implemented and assessed at the scale of whole ecosystems.

A rational strategy to sequester carbon must consider all the components of the terrestrial ecosystem. Single tree species cannot be considered in isolation from other plant species or from soil because of the interactions and interdependencies among species in an ecosystem. Likewise, soil management cannot be separated from plant productivity. This integrative strategy element—ecosystem dynamics—is driven by four basic needs:

- Balance decomposition of biomass and soil organic matter as a source of carbon loss to the atmosphere against decomposition as a source of nutrients essential to plant growth. Sequestration strategies that attempt to decrease decomposition rates may inadvertently result in lower ecosystem carbon storage because, without decomposition, insufficient nutrients are available for plant growth. Plants, soil, and nutrient cycling must be considered together.
- Balance instantaneous or optimum plant productivity with the desire for long-term, predictable/stable productivity. An ecosystem that is managed for a single species likely will not maintain productivity under a wide range of conditions, such as climatic anomalies or disease outbreaks, without intensive management inputs. Target species, species diversity, and ecosystem resilience must be considered together.
- Design strategies that are compatible with other human demands on land and natural resources. It is necessary to understand both the impacts of carbon management on other ecosystem services and ways to design carbon management strategies that work in concert with other goals for terrestrial ecosystems, such as production of food, fuel, and fiber; clean water;

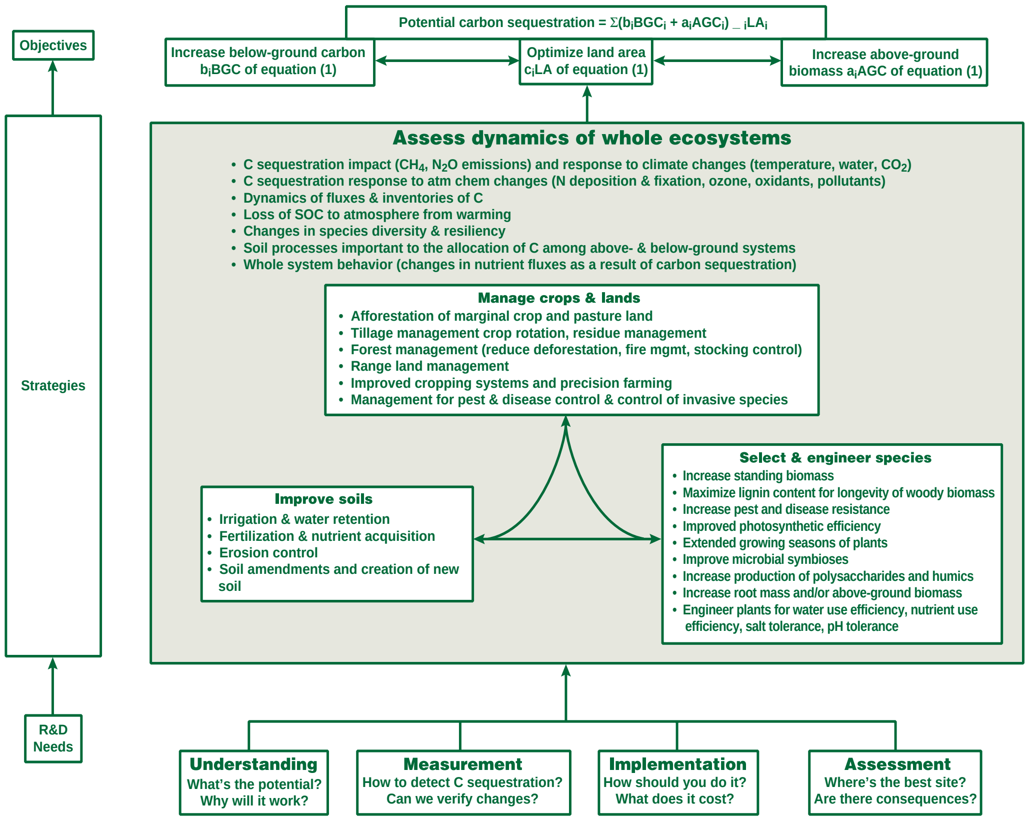


Fig. 4.4. Detailed view of the strategies level illustrating the options for which R&D will be required for effective implementation.

climate moderation; or aesthetic or cultural value.

- Determine the potential feedback from carbon sequestration actions. What is the impact of carbon sequestration on the production or consumption of trace gases that affect radiative forcing (N_2O and CH_4) or that otherwise have significant roles in atmospheric chemistry (CO and NO)? For example, increased organic matter content in wetlands might increase net methane emission. Will increased reservoirs of organic matter in soils significantly affect weathering and subsequent transport in rivers of iron, silica, and other micronutrients? If so, in what direction might changes occur, and what are the potential impacts? What consequences would an emphasis on desert carbon sequestration have on a eolian transport of iron and other metals or nutrients to the oceans or other terrestrial ecosystems?

R&D related to sequestering carbon in soils and vegetation will be diverse and must include integrated assessment to address several features that will influence, or be influenced by, other carbon sequestration strategies. Key features of these assessments will be (1) land use inventories, (2) assessments at scales from watersheds to global, and (3) life-cycle analysis, which is the estimation of all costs (real dollars and carbon costs) to perform R&D and implement carbon sequestration options. Many dynamic parameters and processes must be measured and assessed over time, including

- Carbon sequestration impacts to the atmosphere (e.g., increased CH_4, CO, or N_2O emissions) and responses to climate changes (temperature, water, CO_2), in addition to CO_2 withdrawal by carbon sequestration
- Loss of sequestered soil carbon to the atmosphere as a result of global warming
- Carbon sequestration responses to atmospheric chemistry changes (nitrogen deposition and fixation, ozone, oxidants, other pollutants)
- Dynamics of fluxes and inventories of carbon at all scales as they change with response to carbon sequestration
- Changes in species diversity and resiliency (e.g., if you design a plant species for early rapid growth, you may limit its long-term growth and/or life expectancy) as a response to carbon sequestration
- Soil processes important to the allocation of carbon among above- and below-ground systems (transformations, transport, and fate)
- Whole ecosystem behavior as a response to carbon sequestration (e.g., alteration of nutrient fluxes as a result of a sequestration emphasis, including soils, wind transport of iron and silica to oceans, and transport of organic matter to aquatic systems)

4.4.2.1 Improve soil

A variety of detailed strategies could be implemented or developed to increase the carbon content of soil, increasing below-ground carbon directly and above-ground carbon indirectly. One of the key questions is whether soil texture, topographic position, and climate ultimately determine the carbon content of a soil or whether it can be changed by manipulation. We know little about the processes of humification (formation of humus, which consists of decayed organic matter that provides nutrients for plants and increases the soil's retention of water) or stabilization of decomposable organic carbon in soils. However, our current level of understanding is adequate to begin to address the questions: To what degree can these processes of stabilization be managed? What would be the consequences for plant productivity and ecosystem functions?

Figure 4.4 offers a detailed view of components of the soil improvement strategy. Opportunities for innovation exist in the following areas if R&D can address these key questions:

- **Irrigation and water retention.** How can we minimize the amount of water required, or perhaps use water of lower quality to increase carbon accumulation? For example, groundwater of marginal quality could be used for restoration of large tracts of degraded lands. Urban forests and grasslands would benefit from utilization of "gray" water from homes, businesses, or cities rather than irrigation using potable water supplies. Surface treatments or soil amendments that improve retention of water in soil between rain events and irrigation would also be of great benefit. Could desalination be linked to irrigation and carbon sequestration via production of carbonates with brines and CO_2?
- **Fertilization and nutrient acquisition.** Can we improve the efficiency at which nutrients are taken up by plants through novel

microbial manipulations or soil amendments? Can we determine and enhance the role of mycorrhiza (a mutual association between a fungus and the root of a seed plant it invades) in carbon fixation and plant productivity? We must address the availability of other critical nutrients and trace elements, not just nitrogen and phosphorous.

- **Enhance production and retention of soil carbon.** Can the formation of strongly-adsorbing and highly-recalcitrant organic macromolecules be enhanced through soil amendments, microbial manipulation, or genetic selection of biomass? Can soil organic carbon profiles be deepened to provide a greater mass of soil available for carbon sequestration? Can inorganic carbon formation be enhanced in an arid system?
- **Erosion control.** Beyond no-till agriculture, what methods can be used to minimize soil erosion? Are there soil additions or surface treatments that will significantly inhibit the susceptibility of soils to water erosion? Are there engineering innovations to at least trap organic matter that might be released from erosion (e.g., sediment trapping to enhance wetlands)? Can the current ~0.5 GtC (Stallard 1998) trapped in sediments each year behind dams be permanently sequestered?
- **Soil amendments or creation of new soil.** Can waste byproducts (e.g., fly ash, concrete, sewage sludge) be used alone or mixed with other materials to improve soil characteristics safely and economically to help the retention of carbon? Can materials created from byproducts be used to reclaim degraded lands, or perhaps even help mitigate land subsidence while at the same time sequestering carbon?

4.4.2.2 Manage crops and land

Opportunities for increasing carbon sequestration by management practices vary in intensity and are specific to each ecosystem. There are also complexities to implementing some strategies. For example, no-till practices reduce oxidation of soil organic matter but do not necessarily promote increased incorporation of surface organic matter into the soil to potentially enhance soil organic carbon in the long term. There are opportunities to use natural biodiversity as well. For example, a shift from annual to perennial grains would benefit soil carbon sequestration. Management of agricultural ecosystems by planting trees and legumes mixed with crop plants can add organic carbon to soil. Proposed strategies include:

- afforestation of marginal crop and pasture land
- tillage management, crop rotation, residue management
- forest management (reducing deforestation, improving stocking control, implementing fire management)
- range land management
- improved cropping systems and precision farming focused on soil management
- management for pest and disease control and control of invasive species
- decrease urbanization and land conversion of forests to agricultural use

4.4.2.3 Select and engineer species

Opportunities to select or genetically engineer species for carbon sequestration behavior can directly impact both above-ground and below-ground carbon. It will be important to understand carbon partitioning into biomass as we attempt to engineer or select for carbon sequestration traits. R&D can also indirectly make more land area available for carbon sequestration (e.g., by improving food production per hectare so that more land is available for carbon sequestration). This strategy should include (1) research on plants and microbial communities with a focus on near-term (next 25 years) biotechnology options and species selection using extant knowledge and (2) relevant fundamental research on functional genomics that will have impacts in later years (>50 years).

For research in plant genetics, genes must be available for insertion into the plant of choice. Many genes in agriculture have come from a small set of annual plants (e.g., *Arabidopis*), for which information on gene function (e.g., disease resistance or flower formation) is easily obtained. Most of the genes found in such plants would not have direct value to a carbon sequestration strategy because genes for long-term carbon storage may have little agronomic value. Thus, to enable use of genetic engineering for carbon sequestration, there is a need to discover genes in perennial plants that allocate more carbon to below-ground components, that code for higher content of extractives (components desired from the plant), or that provide resistance to microbial degradation. To enable the discovery of such genes, a functional genomics effort must precede the genetic engineering efforts.

It is not always necessary to start with functional genomics to modify the plant genome. For example, genes for producing higher lignin content in maize have been bred out of current varieties. (Lignin is a complex polymer that hardens and strengthens the cell walls of plants and that does not decompose easily.) Genetic stocks possessing higher lignin content exist, and these could be reintroduced if the objective were to produce this characteristic for carbon sequestration. R&D on altering the Rubisco enzyme to increase biomass production through a more efficient uptake of carbon also might have huge potential benefits. Opportunities in this area and others are discussed in more detail in Chap. 6. Strategies central to this theme include developing methods to

- increase standing biomass
- maximize lignin content for longevity of woody biomass
- increase pest and disease resistance
- improve photosynthetic efficiency
- extend growing seasons of plants
- increase root:shoot ratios
- increase carbon allocation in below-ground components of less decomposable carbon compounds (e.g., lignin, phenolics)
- engineer new plants that have improved water efficiency, nutrient utilization, salt tolerance, and pH tolerance

Metting et al. (1999) provide details on some of the microbial biotechnology options available for sequestering more carbon in soil and vegetation, including species selection and genetic engineering to

- improve microbial symbioses (mycorrhizal fungi, bacterial fixation of nitrogen, and other

nutrient acquisition features of soil)
- grow mycorrhizal fungi in pure culture (especially those that might improve water and nutrient uptake)
- increase production of polysaccharides and humic substances to stabilize soil organic matter

4.4.3 Research and Development Needs

We have now reached the bottom and final level of the road map—science and technology needs. The R&D recommended to address these needs cuts across several ecosystems and is intended to be general so as to stimulate thought rather than prescribe research for investigators. There are four critical aspects to be considered in planning an R&D program to address carbon sequestration in terrestrial ecosystems

Understanding. What is the potential for a given strategy to actually work? What are the scientific principles that govern carbon sequestration?

Measurement. How can we measure the rates of current carbon sequestration by terrestrial ecosystems? Are these rates likely to change significantly as a result of changes in atmospheric chemistry and climate? Can we detect changes in carbon sequestration rates after implementing various strategies? Can these changes be verified at large scales?

Implementation. If a strategy appears feasible, how should it actually be pursued? What advances in engineering are required? What are the costs associated with implementation? These costs can be in terms of actual dollars but also in terms of costs of carbon as fuel or materials (e.g., fertilizer may be required). How can we verify that a particular carbon sequestration implementation is effective and not the consequence of simultaneous changes in other factors?

Assessment. Where are the best opportunities to implement various strategies? What are the possible consequences of implementation over both the short and long term to the landscape, local, regional, or global ecosystems?

Process-level research will directly address the questions that must be answered to increase our understanding of carbon sequestration systems. This research is closely linked to and dependent on research into **measurement and sensing** methods to enable study of processes at a variety of scales. New measurement methods can also lead to new breakthroughs in our understanding of key processes. Advances in measurement and sensing directly support the critical need for verification and monitoring of carbon sequestration. Both of these areas will provide direct benefits to research in **ecosystem response and modeling**. This R&D area primarily links to the needs in assessment and represents an integrative R&D topic. Clearly, advances in **engineering technology** will be required to support the implementation of carbon sequestration strategies. As engineering advances are developed, though, information should be linked to ecosystem response and modeling so as to support assessment. We present specific R&D topics as itemized bullets for clarity to align with the details of the road map found in Fig. 4.5.

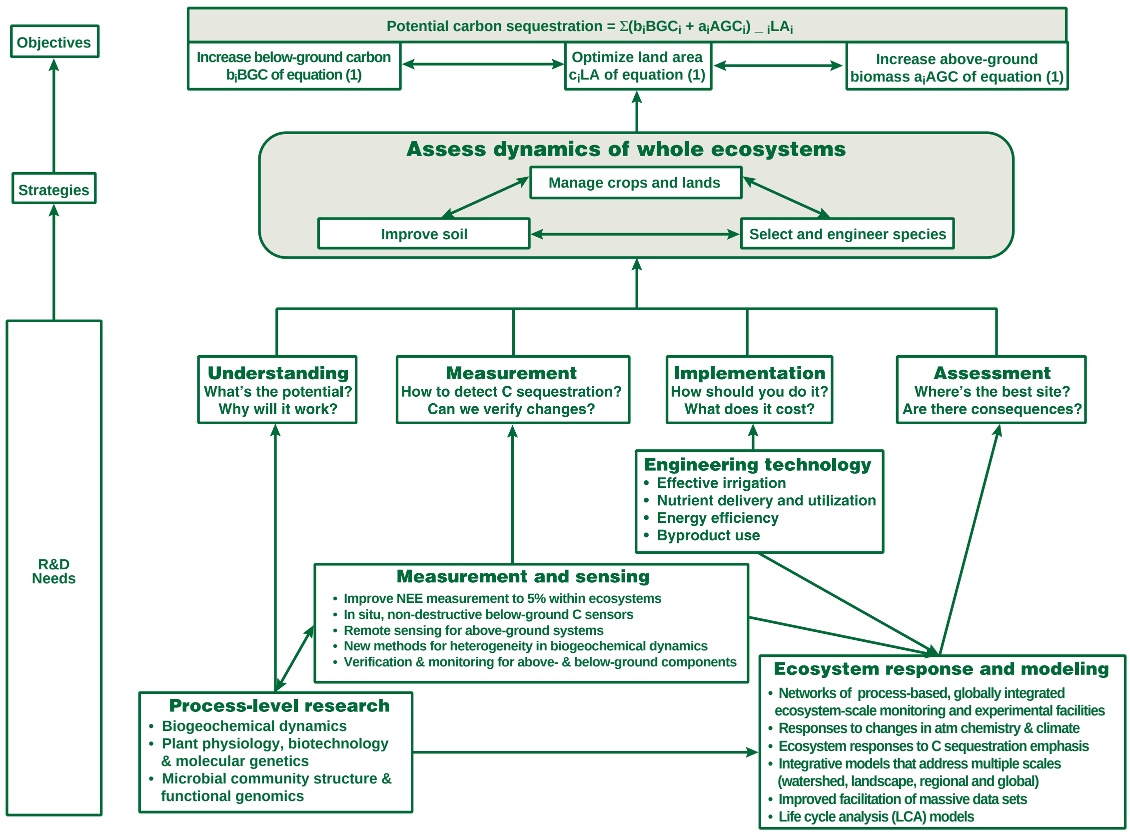


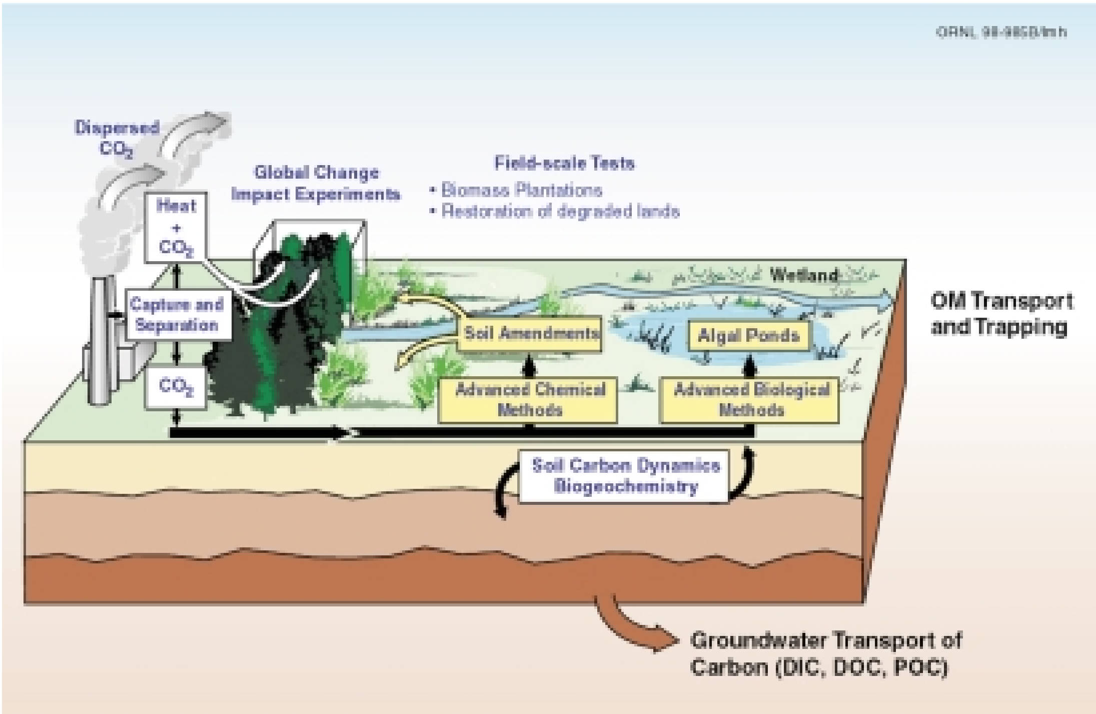
Fig. 4.5. Detailed view of the R&D needs level illustrating the fundamental R&D needed to support the development of carbon sequestration options for terrestrial ecosystems.

4.4.3.1 Process-level research

Process-level research in the following areas will directly aid our understanding of carbon sequestration systems. R&D is needed to focus on the following:

- Biogeochemical dynamics of carbon, nitrogen, phosphorus, calcium, magnesium, potassium, and trace elements that control transformations of carbon and its transport and fate among plants, soil, water, and the atmosphere. The dynamics must be investigated within the context of a system that includes soil, water, plant, microbe, and climate interactions.
- Plant physiology, biotechnology, and molecular genetics. R&D topics would include development of methods to select and engineer plant species for improved nutrient acquisition, growth, carbon density, and/or carbon sequestration. How can we alter the composition of cellular components and design plants for effective byproduct use by increasing energy content, durability, and lignin content to reduce decomposition rates, or recyclability? How can pest and disease resistance be improved? (See also Chap. 6.)
- Microbial community structure and functional genomics. R&D should be directed toward (1) plant

Field-Scale R&D on DOE Reservations



Advancing the science and technology needed to enable the mitigation of climate change resulting from CO_2 emissions through carbon sequestration will require long-term research, evaluation, assessment, and demonstration. DOE lands and associated facilities offer research sites and test beds for evaluating sequestration in terrestrial ecosystems. DOE lands offer great diversity—from shrub-steppe at Hanford, Washington, to tall-grass prairie at Argonne, Illinois, to deciduous forest at Oak Ridge, Tennessee (Brown 1998). Our vision is to have an integrated program of field-scale research, development, and assessment that would allow evaluation of CO_2 separation science and terrestrial sequestration options. Early research at field scale often results in meaningful feedback to guide process-level research. DOE lands represent well-studied sites, offer good opportunities to involve the public in evaluating carbon sequestration, and could assess transportation and other costs of sequestration at a small scale in early studies.

rhizosphere microbial community functions, (2) the microbial community role in stabilizing soil organic matter or slowing decomposition of organic matter, and (3) impact studies of effects of altered soil processes on nitrogen mineralization and fixation and plant acquisition of other nutrients.

4.4.3.2 Measurement and sensing

Developing measurement and sensing techniques to verify the occurrence of carbon sequestration in terrestrial ecosystems and to monitor its effects will be challenging (Post et al. 1998). Methods are needed to ensure that researchers sample sites where the changes are occurring in ways that reduce sampling errors. Detection of changes in terrestrial carbon at large scales will also offer challenges. It is possible that rules of thumb could be determined for carbon sequestration accomplished by certain practices, but at this time the basis for developing quantitative rules is severely lacking. Because of these challenges, we believe the following R&D topics are particularly important.

- In situ, nondestructive below-ground sensors are needed to quantify rates and limits of carbon accumulation both spatially and temporally. Three areas of importance are (1) soil carbon, water, and nutrients as a function of depth; (2) biomass (root and microbial community) imaging; and (3) porosity or soil structure changes. An example of a sensor that might be developed to measure changes in carbon concentrations in soil would be a miniaturized nuclear magnetic resonance imaging device for scanning a volume of soil below ground.
- Remote sensing (e.g., by satellite imaging) is needed for above-ground biomass systems. Improvements are needed in the frequency, accuracy, and scale of measurements to evaluate land cover and management differentiation and address the variability caused by heterogeneity at these scales.
- New methods of extrapolating across the scale of below-ground processes are needed to enable tracking of changes measured in biogeochemical dynamics.
- Verification and monitoring. Will new sensors be required or will process knowledge (rules of thumb) be sufficient to estimate carbon sequestration based on the implementation of observable practices?

4.4.3.3 Engineering technology

Once new concepts based on understanding are put forth, some key engineering issues must be addressed to allow for effective implementation of strategies. We offer the following examples:

- Effective irrigation. How can water usage be minimized? Are there opportunities to develop gray water management for urban areas? How might wetland restoration be combined with waste water treatment? What are the implications of using groundwater of marginal quality?
- Nutrient delivery and utilization. A key issue will be nitrogen fixation. Also, with a mandate to reduce organic matter decomposition, nutrient availability will be an issue. Are there innovative soil amendments that can be developed? How can more litter be incorporated effectively into the soil? Are there ways to use large volumes of animal wastes or sewage sludge to improve carbon sequestration while solving this vexing environmental challenge?
- Energy efficiency. Many carbon sequestration methods will require the use of materials that must be handled with heavy equipment: how can the energy penalty be minimized? What alternatives to classic fertilizers can be developed to avoid the fossil fuel emissions from fertilizer production?
- Byproduct use. There are important R&D links to existing programs. For example, the DOE biomass program is examining fossil fuel displacement and the DOE Office of Industrial Technology is

investigating feedstock programs. Are there innovative options to store or bury harvested biomass products? How can biomass products like wood be included in structural materials (e.g., to replace cement, which is produced by a CO_2–emitting process) to both sequester carbon and reduce CO_2 emissions?

4.4.3.4 Ecosystem response and modeling

The fundamental R&D needed for Ecosystem Response and Modeling falls into two broad categories. First, key measurements will be required for computer models that will evaluate the long-term effects of carbon sequestration. These measurements differ in emphasis from those in Sect. 4.4.3.2 by requiring larger scales, probable manipulative experiments, and integrated measurement strategies. Second, integrative models will be required at scales from landscapes to global ecosystems.

- Networks of process-based, globally integrated ecosystem-scale monitoring and experimental facilities.
- Measurement of plant and ecosystem-scale responses to changes in atmospheric chemistry and climate variables such as CO_2, temperature, water, nutrients, ozone, and pollutants. For example, increases in emissions of CO, N_2O, and CH_4 as a feedback from increased carbon sequestration activities.
- Measurement of ecosystem responses to sequestration. For example, species diversity and resiliency may be affected by implementation of some strategies.
- Integrative models that address plant-, watershed-, landscape-, and ecosystem-scale processes up to regional and global systems. These models must also make use of and facilitate use of massive data sets that will be collected through some of these activities. For example, work is needed to assess possible impacts from a focus on restoration of degraded lands, or carbon sequestration and erosion control in deserts that could reduce transport of iron and silica micronutrients by air currents to the ocean.
- Life-cycle analysis models that can identify opportunities for biomass gains, evaluate social and economic issues, and estimate total system costs (real costs and carbon costs).

4.5 SUMMARY

Carbon sequestration in terrestrial ecosystems will provide significant near-term benefits (over the next 25 years), with the potential for even more major contributions in the long-term (> 50 years). There are many ancillary positive benefits from carbon sequestration in terrestrial ecosystems, which are already a major biological scrubber for CO_2. The potential for carbon sequestration could be large for terrestrial ecosystems (5–10 GtC/year). However, this value is speculative, and a primary R&D need is to evaluate this potential and its implications for ecosystems. In addition, economic and energy costs were not fully considered in the analysis to estimate the carbon sequestration potential. As carbon sequestration strategies are developed, a whole ecosystem approach under changing climate conditions must be considered. Potential feedback mechanisms (both positive and negative) must be addressed.

Our primary focus has been on manipulative strategies to increase carbon sequestration rather than protect ecosystems. We wish to emphasize that carbon stored below ground is more permanent than plant biomass. However, even soil carbon must be managed in the long term. One of the key questions is whether soil texture, topographic position, and climate ultimately determine the carbon content of a soil, or whether it can be permanently changed by manipulation and to what extent. For plant biomass, transformation of carbon into long-lived products or below-ground storage is essential. With this perspective, it appears that the following ecosystems offer significant opportunity for carbon sequestration (not in any order of priority):

- **Forest lands.** The focus should include below-ground carbon and long-term management and utilization of standing stocks, understory, ground cover, and litter.
- **Agricultural lands.** The focus should include crop lands, grasslands, and range lands, with an emphasis on increasing long-lived soil carbon.
- **Biomass croplands.** As a complement to ongoing efforts related to biofuels, the focus should be on long-term increases in soil carbon.
- **Deserts and degraded lands.** Restoration of degraded lands offers significant benefits and carbon sequestration potential in both below- and above-ground systems.
- **Boreal wetlands and peatlands.** The focus should include management of soil carbon pools and perhaps limited conversion to forest or grassland vegetation where ecologically acceptable.

In developing the road map, we established three interrelated objectives that transcend ecosystems: increase below-ground carbon (soil carbon), increase above-ground carbon (plant biomass), and optimize land area for sequestration of carbon.

These objectives can be accomplished by the following strategies: improve soil characteristics, manage crops and lands for sequestration, and select and engineer species for sequestration. These three strategies must be considered from the perspective of whole ecosystems, which is the scale at which management for optimizing carbon sequestration will be accomplished.

Research on four key interrelated R&D topics is needed to meet goals for carbon sequestration in terrestrial ecosystems:

1. **Increased understanding** of ecosystem structure and function directed toward carbon allocation and partitioning, nutrient cycling, plant and microbial biotechnology, molecular genetics, and functional genomics.

2. **Improved measurement** of large-scale carbon fluxes, dynamic carbon inventories with the development of new or improved instrumentation for in situ, nondestructive below-ground observation, remote sensing for

above-ground biomass measurement, and verification and monitoring of carbon stocks.

3. **Implementation of improved knowledge and tools** such as better irrigation methods, efficient nutrient delivery systems, increased energy efficiency in agriculture and forestry, and increased byproduct use.

4. **Assessment of ecosystem responses** to changes in both atmospheric chemistry and climate, and other processes that might be impacted by implementation of carbon sequestration strategies. Suites of models would be used, integrating across scales ranging from physiological processes to regional scales as inputs to global-scale modeling and including life cycle analysis models.

Finally, field-scale research should be implemented in the near term with manipulations in large-scale ecosystems aimed at clarifying both physiological and geochemical processes regulating carbon sequestration. This research should be closely linked to integrative ecosystem modeling. The creation of such carbon sequestration test facilities on DOE reservations would provide proof-of-principle testing of new sequestration concepts and an integration of diverse sequestration science and engineering challenges.

4.6 ACKNOWLEDGMENTS

All members of the team who helped develop this chapter are identified in Appendix A. In addition, we express our appreciation to the following individuals who provided thorough and meaningful review comments: Gary King, Linda Mann, David Nowak, Richard Pouyat, Jerry Tuskan, Donn Viviani, and Stan Wullschleger. We also acknowledge the participants in the September 1999 workshop who helped us improve this chapter.

4.7 END NOTES

The workshop that was conducted during September 1999 was intended to solicit discussion from a broad set of stakeholders. Many of the comments and suggestions have been incorporated into this revised chapter. However, some of the points of consensus we have left in the rapporteur reports summarized in Chapter 9. We feel that these important observations will be more visible as part of these brief reports, rather than blended into this long chapter. The rapporteur report is intended to complement and augment this chapter.

Sarmiento and Wofsy (1999) have recently released a report *A U.S. Carbon Cycle Science Plan*. Their report is an important complement to sequestration R&D plans. Understanding the carbon cycle is important as various carbon sequestrations strategies are developed.

As discussed in Chaps. 1 and 2, several activities include R&D planning for carbon sequestration. One specific event that paralleled this road map activity, with a topic of close relevance, was the workshop entitled “Carbon Sequestration in Soils: Science, Monitoring and Beyond.” This workshop, organized by Oak Ridge and Pacific Northwest National Laboratories and the Council of Agricultural Science and Technology, was held December 3–5, 1998. It addressed the role of carbon sequestration in soils in far greater detail than does this road-mapping exercise. By engaging several participants in that workshop in our effort, we have tried to maintain a consistent view of the most important R&D topics. For excellent and detailed discussions on specific topics, consult the papers prepared for the workshop: Lal, Hassan, and Dumanski; Marland, McCarl, and Schneider; Metting et al.; and Post et al.

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